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TECHNICAL REPORT 233-9

THE CONCEPT OF EROSION STRENGTH

By

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NOTATION

A_e	Area of erosion
C_l	Velocity of sound in liquid
C_m	Velocity of sound in material
E_a	Energy absorbed by material
E_m	Modulus of elasticity of material
l	Average depth of erosion
I	Intensity of erosion
p	Water hammer pressure
S_e	Erosion strength
t	Time of erosion
U_I	Impact velocity
Y_D	Dynamic yield strength of material
z_l	Acoustic impedance of liquid
z_m	Acoustic impedance of material
α	A factor tending to unity at high velocities
ΔV	Volume eroded
ρ_l	Liquid density
ρ_m	Material density
σ_e	Endurance limit of material

SUMMARY

In general, the problem of erosion of materials can be divided into two categories. One is the understanding of the threshold for each material wherein the impact stresses reach a limiting value just sufficient to initiate detectable erosion either at the first blow or after repetitive blows. Evidence is presented to show that the dynamic yield strength of a material controls the threshold for the single impact; whereas, the endurance limit is the important property representing the threshold in the multiple impact case.

The second problem is the prediction of the amount of damage if the erosive forces are above the threshold for the material. The designer needs some numerical value of a property that governs the volume of erosion of a material. As of now, there is no single property that can be used for this purpose, just as we use various properties of materials to represent their response to static, fatigue and creep loadings. A recent suggestion to use the strain energy of the material, as given by the area of the stress-strain diagram from a simple tensile test, for this purpose has a few limitations such as strain rate effects, environmental effects (e.g. temperature and corrosion) and the scarcity of stress-strain data under these conditions. In order to overcome these limitations, a new concept known as erosion strength is introduced, and it is defined as the energy absorbed per unit volume of material up to fracture

under the action of the erosive forces in various environments. The methods to determine the erosion strength from an erosion test are outlined.

If accepted by the engineering profession, the concept of erosion strength would take a place among the other mechanical properties of materials such as yield strength, ultimate strength, fatigue strength, creep strength, hardness, corrosion fatigue, etc.

INTRODUCTION

The word "erosion" from the Greek "erodere" -- to gnaw away -- generally means the surface destruction and removal of material by external mechanical forces. In the majority of practical cases, these forces are in the form of multiple impacts produced by the dynamic impingement of a liquid on a solid surface or of a solid on another solid surface. Numerous examples may be cited where such phenomena are important. For example:

(i) Cavitation damage of hydrodynamic systems such as hydraulic turbines, ship propellers, valves, etc.,

(ii) Erosion of steam turbine blades due to the impact of condensed liquid droplets,

(iii) Erosion of aircraft structures as a result of collisions with rain drops.

(iv) Sand erosion of water turbines and other control devices, and

(v) Erosion of space vehicles as a result of impacts with meteorites.

In all of these erosion problems, one of the important aspects is the prediction of the material response to a given set of input conditions such as the collapse of a bubble on or near the surface, the impingement of a liquid drop or jet, the impact of a solid particle. In general, the impact energy of the input system will produce on the material one of the following effects depending upon the intensity of impact and the number of repetitions, (See Figure 1):

- (i) There may not be any permanent deformation;
- (ii) The material may deform after a certain number of repetitive impacts;
- (iii) A permanent deformation may develop at the onset of the first blow; and
- (iv) It may plastically flow on the first blow itself or after a certain number of repetitions as a result of high strain rates.

Based on these arguments, one can arrive at two types of problems. The first one is the understanding of the threshold conditions wherein the impact stresses reach a limiting value just sufficient to initiate detectable erosion either at the first blow or after repetitive blows. The second case is the prediction of the amount of damage if the erosive forces are above the threshold for the material. It is the aim of most of the investigations to provide the designer with numerically expressed properties to represent the behavior of the materials under the above two cases. The property (or properties) that

control the threshold conditions, wherein the criterion is the observable yielding of the material, need not be the same as the property that represents the volume of erosion of a material wherein the material is being fractured and removed from the surface. It is the purpose of this report to discuss these two cases in the light of some of the results obtained in our laboratory in connection with cavitation erosion as well as those published in the literature.

It is found that the dynamic yield strength and the endurance limit are the two properties controlling the threshold conditions due to single impact and multiple impacts, respectively. However, the volume of erosion when the erosive forces are above this threshold, is controlled by some property of the material that represents the energy absorbing capacity of the material. Recent attempts (1,2) to correlate the strain energy of the material from the simple tensile test are handicapped by a few limitations such as strain rate effects, environmental effects and the scarcity of the stress-strain data under these conditions. To overcome these difficulties, the concept of erosion strength is introduced with methods of determining this erosion strength from an erosion test. In many practical cases, the erosion forces may be assisted by environmental effects such as corrosion, embrittlement, temperature, etc., and the methods to determine the erosion strength under these conditions are also outlined.

THRESHOLD CRITERIA

It is becoming increasingly common to observe a threshold parameter such as the threshold intensity of cavitation damage, the threshold amplitude of oscillation, the threshold velocity of flow, the threshold impact velocity etc., in erosion problems such as cavitation damage, turbine blade erosion, rain erosion, jet or drop impact erosion. When a cylindrical column of liquid impinges on the surface of a material, the maximum pressure (generally known as the "water hammer" pressure) developed by the impact is given by de Haller (see for example Reference 3) as

$$p = \frac{\rho_l C_l U_I}{1 + \frac{\rho_l C_l}{\rho_m C_m}} \quad [1]$$

where

U_I is the impact velocity,

ρ_l is the density of liquid,

ρ_m is the density of material,

C_l is the velocity of sound in liquid, and

C_m is the velocity of sound in the material.

For most practical cases of liquids and materials involved, the ratio of $\rho_l C_l / \rho_m C_m$ is small and this term may be neglected. Then the water hammer pressure becomes

$$p = \rho_l C_l U_I \quad [2]$$

Such an estimate for a spherical liquid drop colliding with a solid surface has been given by Engel (4) as

$$p = \frac{\alpha}{2} \rho_l C_l U_I \quad [3]$$

where α is a factor tending to unity at high velocities; the factor $1/2$ is due to the spherical shape of the drop.

Experiments by Brunton (6,8) show that the measured values of the pressures closely agree with the values predicted by the water hammer equations.

The threshold criterion for the case when a drop makes a single impact on a metal would be that the water hammer pressure should exceed the dynamic yield strength of material producing a detectable permanent deformation (9). It may be mathematically stated as

$$\frac{Y_D}{\rho_l C_l U_I} = \epsilon \quad [4]$$

where Y_D is the dynamic yield strength of the material. However, in practice, the material deformation starts after repeated multiple impacts. In such a case, if we assume that the significant material property would be the endurance limit of

the material, then the threshold criterion is modified as

$$\frac{\sigma_e}{\rho_l C_l U_I} = 2 \quad [5]$$

where

σ_e is the endurance limit.

There are a few published data for multiple impact of water drops on metals (5,7) and the results are summarized in Table 1. These data seem to check well with the criterion given by Equation [5] which states that the endurance limit of the metal is the property controlling the threshold.

Even in cavitation damage, the threshold is characterized by the endurance limit of the metals (1,13). Earlier experiments (1) with a two-dimensional water tunnel and with a rotating disc apparatus showed that the threshold velocity of flow depended upon the endurance limit of metals. Recent experiments with a magnetostriction oscillator producing cavitation on an oscillating piston also showed that the endurance limit of metals controls the threshold intensity of cavitation damage (13).

There are no similar experiments to verify whether the threshold conditions in solid-to-solid-erosion problems such as sand erosion, also are represented by the endurance limit of the materials. However, Leith and McIlquham (14) report that sand erosion can be correlated with cavitation damage erosion.

While the foregoing discussion tends to establish the endurance limit as the sole material property controlling the threshold conditions in a multiple impact test, there is a differing point of view wherein the modulus of elasticity also would become important. Engel (15) gives the following relationship for the threshold velocity of a liquid drop to produce a dent in the metal:

$$\dot{U}_I = \frac{19 Y_D (z_l + z_m)}{(\rho_l C_m z_m^3)^{\frac{1}{2}}} \quad [6]$$

where

$z_l = \rho_l C_l$ of liquid,

$z_m = \rho_m C_m$ of material.

Equation [6] can be rewritten in the form

$$U_I = \frac{19 Y_D}{\rho_l^{\frac{1}{2}} E_m^{\frac{1}{2}}} \quad [7]$$

Since

$$C_m = \frac{E_m^{\frac{1}{2}}}{\rho_m^{\frac{1}{2}}}$$

where

E_m is the modulus of elasticity of the material.

For multiple impacts of drops, Y_D can be replaced by the endurance limit (as before), giving

$$U_I = \frac{19 \sigma_e}{\rho_l^{\frac{1}{2}} E_m^{\frac{1}{2}}} \quad [8]$$

Now the threshold criterion would become as

$$\frac{\sigma_e}{U_I \rho_l^{\frac{1}{2}} E_m^{\frac{1}{2}}} = 0.05 \quad [9]$$

It is interesting to study the relationships (5) and (9). While Engel finds the relationship (6) to hold good for 1100 aluminum, the data shown in Table 1 do not agree with the value of 0.05 in Equation [9]. This discrepancy brings forth the necessity to conduct more investigations and to verify whether the modulus of the material is really an important parameter as shown by Equation [9].

NECESSITY FOR THE CONCEPT OF EROSION STRENGTH

So far the discussion was confined to the threshold conditions at which the materials start damaging and their relationship to dynamic yield strength, and endurance limit (including modulus of elasticity). It was also pointed out that there are

some misgivings about the significance of the modulus of elasticity. Once this question is resolved, the easiest design approach would be to determine the threshold values and use the proper materials. However, it is not always possible to limit the designs to the threshold conditions. Practical and economic considerations may warrant a design in which we may have to live with some erosion in a given material and predict the life of the system. In this case, it is essential to know the property of the material that controls the volume that is eroded in a given time.

There have been several attempts to correlate the resistance of a material to erosion with any one of its known mechanical properties such as yield strength, ultimate strength, hardness etc., without much success. The evidence for this statement may be found in Reference 16 for cavitation damage and (5,7) for drop impact erosion. This situation led to a premise [to quote from Peterson (17)] that "it is not possible to provide the designer with numerically expressed 'properties' which can be fed into formulas for proportioning parts, as one can do for static, fatigue and creep loadings". Qualitative and comparative screening tests led to a duplication of efforts in addition to confusing the problems involved.

Recent analysis (1,2) in connection with cavitation damage pointed out that the property correlated should represent the energy absorbing capacity of the material up to fracture. Available experimental results showed that the strain energy of

a material up to fracture as given by the area of the stress-strain diagram represents the erosion resistance as far as cavitation damage is concerned. However, there are a few genuine limitations to this approach namely:

(i) The strain rate effects. The strain energy values used for these correlations were obtained at relatively low strain rates; whereas, the erosion phenomena generally takes place at high strain rates. This effect could become very important for strain rate sensitive materials.

(ii) The mode of stressing in erosion is radically different from the simple tensile test.

(iii) The environmental effects such as corrosion, high temperature, vacuum, low temperature and embrittlement can not be quantitatively reproduced in the strain energy measured from a simple test.

(iv) Above all, the availability of the stress-strain data up to fracture under these conditions itself is a great limitation. This is mainly because the strain energy itself is not a commonly used material property. However, its importance is being increasingly felt as the understanding of fracture mechanics progresses.

In order to overcome these limitations, the concept of erosion strength is introduced. Just as yield strength, ultimate strength, fatigue strength, all define a certain physical state and behavior of the materials, the erosion strength is

specifically defined to represent the erosion resistance of materials. It is hoped that this direct approach would lead to a more generalized understanding of the phenomenon of erosion as a whole.

DEFINITION OF EROSION STRENGTH

During the process of erosion, a certain volume of material is fractured from the surface of the parent material as a result of the work done by the external forces. The energy absorbed by the volume of the material fractured is given by

$$E_a = \Delta V \cdot S_e \quad [10]$$

where

S_e is defined as the erosion strength which represents the energy absorbing capacity of the material per unit volume under the action of the erosive forces,

ΔV is the volume of material eroded, and

E_a is the energy absorbed by the material eroded.

The measurement of ΔV in a laboratory experiment is not very difficult. If we can devise a method by which we can accurately determine the energy absorbed by the material under the action of erosive forces, then the erosion strength as defined here can easily be determined.

DETERMINATION OF EROSION STRENGTH

The logic behind the method of determination of erosion strength will be developed by illustrating the specific case of cavitation damage. In this case, the eroding forces are caused by the collapse of cavitation bubbles near the material surface. Recent experiments show that the rate of volume loss is inversely proportional to the strain energy of the material for a group of materials (2) as shown in Figure 2. For five metals in this group, the strain rate effects are shown to be not very important in the experimental investigations on the high frequency fatigue of these metals (18). These experiments were carried out in a magnetostriction apparatus at 14 kcs as described in Reference 19. It is known that both in cavitation damage tests and in liquid impact tests (19,20 and 7), the rate of damage is time dependent in the initial "zones of damage", and it finally reaches a steady state. Successful correlations have been obtained only in the steady state zone.

If one defines the intensity of erosion as the power absorbed by the material per unit area then the intensity I is given by

$$\begin{aligned} I &= \frac{\Delta V}{A_e} \cdot \frac{S_e}{t} \\ &= \frac{1}{t} \frac{S_e}{A_e} \end{aligned} \quad [11]$$

where

A_e is the area of erosion,
 t is the test duration, and
 i is the average depth of erosion.

In our cavitation erosion test, the relationship between the rate of erosion and the amplitude of vibration is obtained as shown in Figure 3 (21). The intensity of erosion was calculated by assuming that the erosion strength is identically the same as the strain energy for the group of materials shown in Figure 2. The correlation shown in this figure provides the justification for the above assumption. Furthermore, the high frequency fatigue tests mentioned earlier show that the materials such as 316 stainless steel, monel, tobin bronze, 2024 aluminum and 1100 aluminum do not exhibit significant effects of strain rates (18). The same group of materials (or just one among this group) may be used to determine the intensity of erosion of a given test device under a set of test conditions. We may call this procedure the calibration of the test device wherein we obtain the numerical value of the intensity of erosion of the test device. Once such a calibration is accomplished, the erosion strength of any material may be experimentally determined by measuring the rate of depth of erosion with this calibrated test device from Equation [11].

This procedure is feasible with any type of erosion whether it is cavitation, liquid impact or solid impact erosion. It may even be extended to wear of materials due to friction.

ENVIRONMENTAL EFFECTS ON EROSION STRENGTH

It is realized that the erosion strength will be affected by various environments such as corrosion, temperature, and vacuum just as other strengths like fatigue, creep, yield, and ultimate strengths are affected by these environments. The main problem in such cases is the determination of the intensity of erosion caused by the erosive forces from the purely mechanical point of view. Once this value is known, then the measurement of the rate of depth of erosion will give the erosion strength in that environment taking into account the environmental effects.

In the following example, the procedure adopted to determine the erosion strength of materials under cavitation in NaCl solutions is illustrated. Figure 3 shows the results of erosion tests in a magnetostriction oscillator using different concentrations of NaCl including distilled water (zero concentration)(21). From these data one can infer that the intensity of cavitation damage is not affected by the concentration of NaCl up to 9 percent and it is the same as in distilled water. If we use a steel specimen instead of aluminum in the same experiment using 3 percent NaCl solution, the erosion increases three fold as compared to distilled water [Table 2, (21)]. The erosion strength is reduced to one third of that in distilled water. It is interesting to compare this result with the corrosion fatigue data obtained at the same frequency in 3 percent NaCl solution as shown in Figure 4 (18).

The same approach may be extended to other environments and liquids. Another interesting case is the determination of the cavitation erosion strength of materials in high temperature liquid sodium (22,23). The strain energy value of 316 stainless steel at the test temperature was used to estimate the intensity of erosion. The erosion strength of other metals for which even the simple tensile properties are scarce in these environments may easily be determined by this method.

CONCLUSIONS

While the threshold conditions of erosion may be correlated to existing properties such as dynamic yield strength and endurance limit, there is no common property that can be used for predicting the volume of the material eroded due to fracture of material from its surface. Recent suggestions to use the strain energy of the material have a few limitations such as strain rate effects, environmental effects and availability of strain energy values. The concept of erosion strength is introduced specifically to overcome these limitations and to provide the designer with some numerically expressed property for designing erosion resistant structures. The methods to determine the erosion strength in various environments are outlined. Although the examples used for the discussion mostly pertain to cavitation erosion, it is believed that these methods can be equally applied to any type of erosion tests involving liquid and solid impact phenomena.

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TABLE 1
Experimental Results Closely Agreeing With
The Threshold Criterion Formulated in This Report

Present Theory $\frac{\sigma_e}{\rho_l C_l U_I} = 2$; Engel's Theory $\frac{\sigma_e}{U_I \rho_l^2 E_m} = 0.05$

E_m = Modulus of Elasticity of Material

No.	Material	Liquid	Impact Velocity U_I - fps	Density of Liquid ρ_l slugs ft ³	Velocity of Sound C_l - fps	Dynamic Yield Strength Y_D - psi	Modulus of Elasticity E_m - psi	Endurance Limit σ_e - psi	$\frac{\sigma_e}{\rho_l C_l U_I}$	$\frac{\sigma_e}{U_I \rho_l^2 E_m}$	Reference
1	Copper	Water	99 (30m/sec)	Value of $\rho_l C_l U_I = 5750$ psi (=4kg/mm ²)		21500 (15 kg/mm ²)	10×10^6	12,000	1.85	0.25	10
2	Steel	Water	200 (60m/sec)	$\rho_l C_l U_I = 17100$ psi (= 12 kg/mm ²)		72000 (50 kg/mm ²)	30×10^6	36,000	2.1	0.18	10
3	Chromium Steel	Water	400	1.94	4500	---	30×10^6	50,000	1.9	0.19	11
4	Stellite C	Water	600	1.94	4500	---	30×10^6	80,000	2	0.20	11
5	Stellite 6	Water	1100	1.94	4500	---	30×10^6	80,000	1	0.10	7(p. 4-4)
6	Chromium Steel	Water Single Impact	600-900	1.94	4500	---	30×10^6	---	2	0.4	12
7	Stellite C	Water Single Impact	1100-1200	1.94	4500	---	30×10^6	---	2	0.2	12

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TABLE 2

Erosion Strength of 1020 Steel in NaCl Solution
(Data from Reference 21 are used;
Nomogram of Reference 13 is also used)

- | | |
|---|--|
| 1. Intensity of Erosion at the
Test conditions using 1100-F
Aluminum (See Figure 4) | $I = 0.3 \text{ watt/meter}^2$ |
| 2. Average Depth of Erosion of
1020 Steel in Distilled
Water | $\frac{1}{t} = \sim 2.5 \text{ inches per year}$ |
| 3. Average Depth of Erosion of
1020 Steel in 3 percent NaCl
Solution | $\frac{1}{t} = \sim 7 \text{ inches per year}$ |
| 4. Erosion Strength of 1020 Steel | $S_e = \frac{It}{l}$ |
| In Distilled Water | In 3 percent NaCl Solution |
| $S_e = 20,000 \text{ psi}$ | $S_e = 7,000 \text{ psi.}$ |

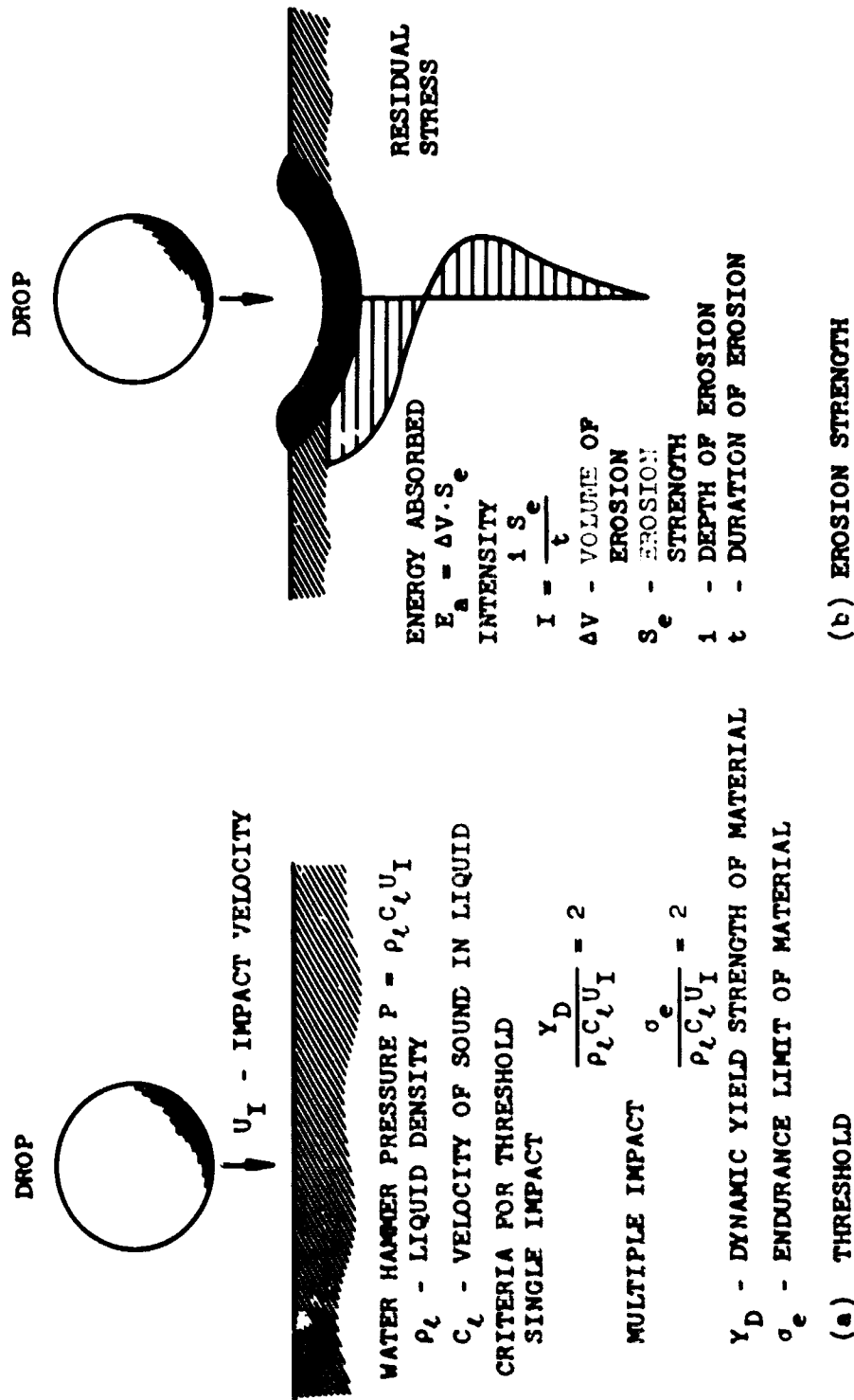


FIGURE 1 - DEFINITION SKETCH FOR THE MATERIAL RESPONSE TO EROSION FORCES

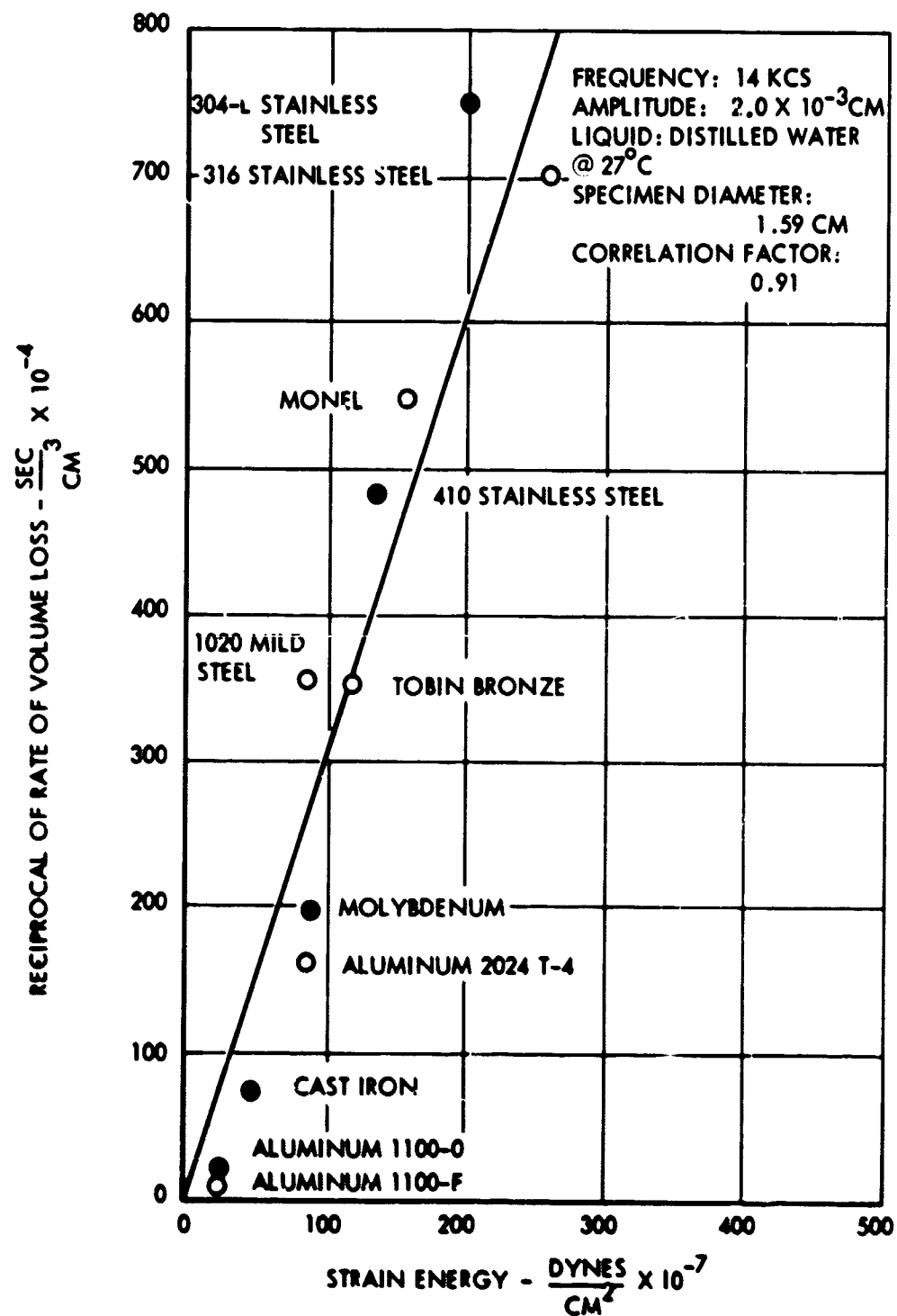


FIGURE 2 - CORRELATION BETWEEN STRAIN ENERGY AND
RECIPROCAL OF RATE OF VOLUME LOSS
[REFERENCE (2)]

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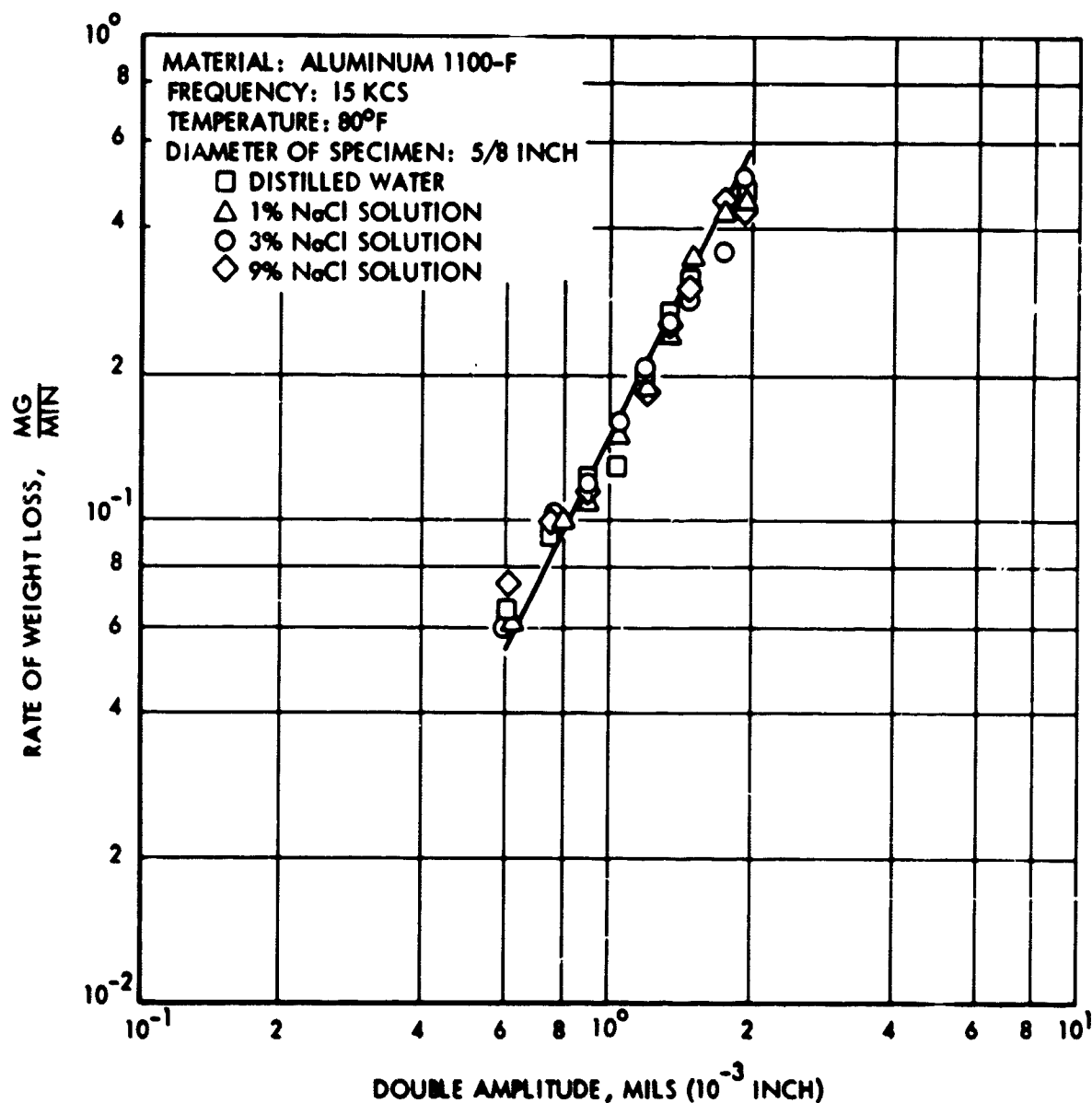


FIGURE 3 - EFFECT OF NaCl CONCENTRATION ON THE AMPLITUDE VERSUS DAMAGE RATE RELATIONSHIP FOR ALUMINUM 1100-F IN STEADY STATE ZONE

[REFERENCE (21)]

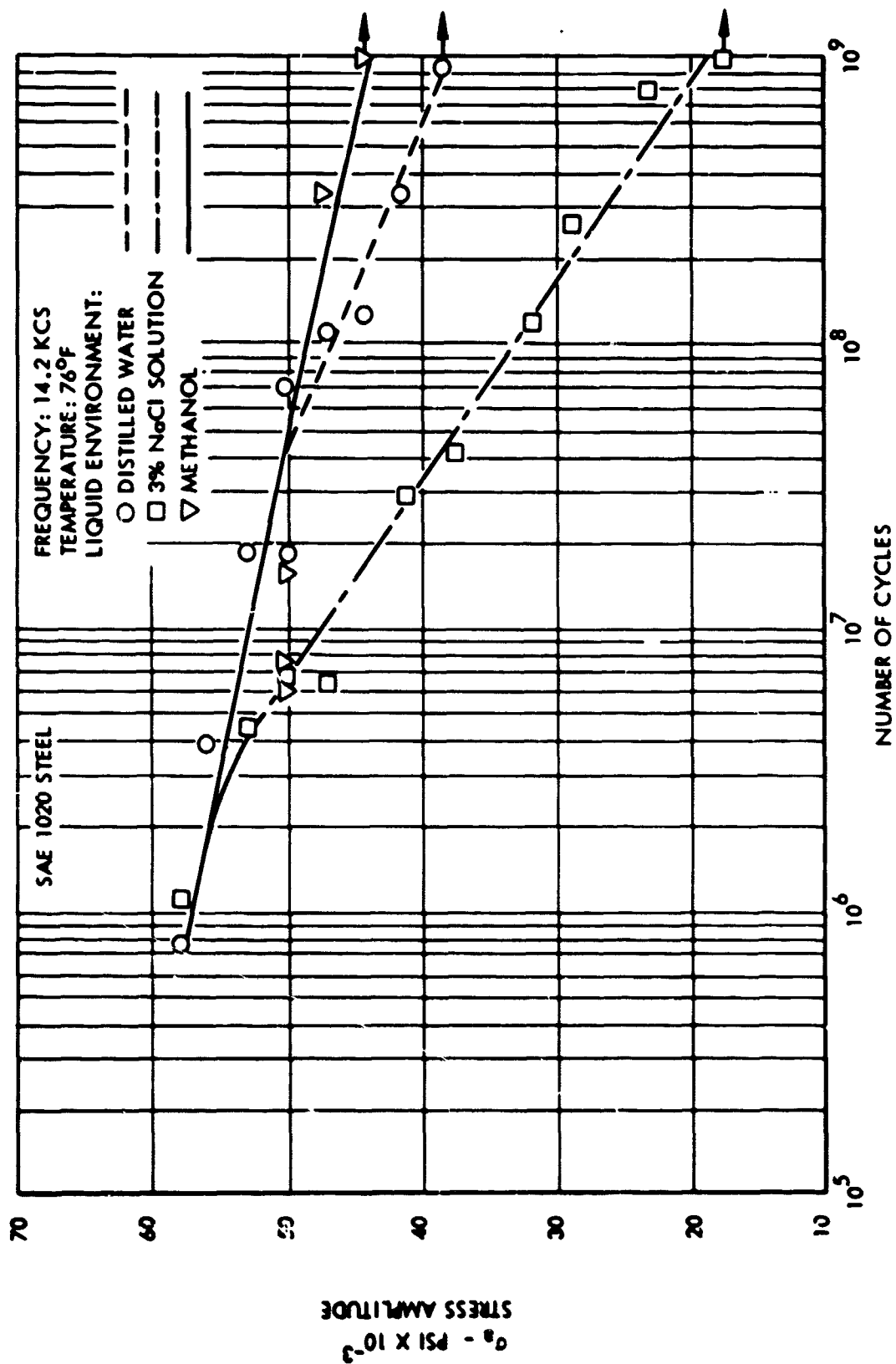


FIGURE 4 - HIGH FREQUENCY CORROSION FATIGUE OF SAE 1020 STEEL
[REFERENCE (18)]

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13. ABSTRACT The designer needs some numerical value of a property that represents the erosion resistance of a material. As of now, there is no single property that can be used for this purpose just as we use various properties to represent static, fatigue and creep loadings. Recent suggestions to use the strain energy of the material as given by the area of the stress-strain diagram from a simple tensile test for this purpose have a few limitations such as strain rate effects, environmental effects (temperature and corrosion) and the scarcity of stress-strain data under these conditions. In order to overcome these limitations, a new concept known as erosion strength is introduced and it is defined as the energy absorbed by the unit volume of a material up to fracture under the action of the erosive forces in various environments. The methods to determine the erosion strength from an erosion test are outlined.		

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	ROLE	WT	ROLE	WT	ROLE	WT
Erosion strength						
Threshold of erosion						
Intensity of erosion						
High frequency fatigue						
Corrosion fatigue						
Strain energy						

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